



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Diagnostic Use of Digital Image Correlation in High-Speed, Explosive Experiments

F. J. Gagliardi, B. J. Cunningham, L. Ferranti Jr.

April 8, 2010

SEM Annual Conference & Exposition on Experimental and
Applied Mechanics
Indianapolis, IN, United States
June 7, 2010 through June 10, 2010

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

Diagnostic Use of Digital Image Correlation in High-Speed, Explosive Experiments

Franco J. Gagliardi, gagliardi7@llnl.gov
Bruce J. Cunningham, cunningham1@llnl.gov
Louis Ferranti, Jr., ferranti1@llnl.gov

Lawrence Livermore National Laboratory
Energetic Materials Center
P.O. Box 808, L-282, Livermore, CA 94550, USA

ABSTRACT: Digital image correlation (DIC) was used as a diagnostic tool in two series of scaled explosive experiments. In this paper, we focus on the use of DIC as a tool to obtain full-field displacement measurements during high-speed events. From the displacement records we were able to obtain full-field strains, strain-rates and velocity data. The experiments discussed in this paper involved explosive charges submerged in aquarium-like structures, one side of which consisted of a 6061-T6 aluminum plate. In each experiment, the outside of the aluminum plate was patterned so that it met the requirements for use with the DIC system. Two different plate preparation techniques were used in the experimental series and both resulted in the acquisition of quality data. While both techniques were effective, each proved to have unique advantages. The details of plate preparation and a discussion of the performance of each method are included in the paper. The displacement, strain and velocity data are discussed and the output capabilities of the DIC system are demonstrated. In addition to the high-speed, transient data acquired during the deformation events, static, surface-profile measurements of the post-test, deformed plates were made using the DIC system. A discussion of the static measurements is also presented.

INTRODUCTION

Explosive blast mitigation is an area of research that is important because it can be used to make better structural designs that are less susceptible to malicious activity [1-6]. Computer models are often used in the design process in an effort to predictively characterize the behavior of a design to certain forms of energetic input, such as that experienced when a structure is impacted with the pressure released from the detonation of a high explosive material. To ensure that computer models are reliable, they need to be validated and tuned with experimental data to ensure that they are properly accounting for the complex nature of the physical phenomena associated with the experiments. This combination of experimental data and computer models is a valuable asset in the fight against those seeking to do damage. Ideally, full-scale models of proposed structures would be tested to determine their response to various stimuli but cost and space are usually prohibitive for evaluating this type of structure. Due to the impracticality of doing explosive tests on full-scale structures to determine their response, scaled experiments are conducted. Much thought is needed in order to develop scalable tests because of the complexity related to the boundary conditions and the pressure application.

This paper reports the results from two series of laboratory-scale experiments in which several forms of blast mitigation were used in order to validate and tune models that will be used to model a large-scale structure. The tests reported include six tests that used one of two different models of an aquarium-like structure. The so-called aquariums had one of their sides made from aluminum 6061-T6. The outside surfaces of the aluminum plates

were prepared for use with digital image correlation (DIC) and were imaged using high-speed photography during the explosive event. The dynamic deformation was monitored and the post-test plastic deformation of each plate was measured using DIC. The results from the two series are presented in the following sections.

EXPERIMENTS

Two series of tests were run to evaluate several blast mitigation techniques in which digital image correlation was used as a primary diagnostic tool. The first series used a cube-like aquarium volume of about 11.5-liters of de-ionized water mixed with a small weight percent of surfactant. The second series used an aquarium-like structure that held a volume of about 265-liters. The experimental assembly is discussed for each in the following subsections.

Small Aquarium Series: Set-up and Tank Configuration

The first series of experiments consisted of the small aquarium variant of the explosive assembly. This assembly, except for the fourth experiment, was made up of a five-walled container, four walls of which were made out of 6.35-mm Lucite and the fifth made out of 3.2-mm thick aluminum 6061-T6. The fourth aquarium had another Lucite wall added so that the Lucite portion alone could contain the water, which would provide the opportunity for a purely air barrier to be created as will be discussed below. The assembled container had a volume of approximately 11.5-liters. The aluminum plate used as one side of the aquarium was 61-cm wide by 61-cm tall. The plate had holes drilled through it so that when attached, the Lucite portion of the aquarium would be centered. Additional holes were drilled near the top and bottom of the plate so that it could be reinforced with Unistrut[®] beams.

In all of the small aquarium experiments the explosive material used was LX-14, which is composed of 95.5% of the explosive HMX and 4.5% of the polymer binder Estane. The charges each weighed about 6.3-g and were in the shape of right-circular cylinders. The explosive charge was positioned in the assembly so that there was a standoff of about 7-cm. Fig. 1 shows a side-view diagram of each of the small aquariums highlighting the blast mitigation technique used. In the first experiment, represented in diagram 1, no mitigation was used, and thus only water existed between the explosive train (LX-14 main charge, shown in purple, and the detonator, shown in black) and the aluminum plate. In the second experiment, shown in diagram 2, air-filled plastic tubes were used as the mitigation type. The tubes had a nominal outer diameter of 6.35-mm and a wall thickness of about 1-mm. The tubes were arranged in an array about 7-cm thick and they were stacked the full height of the aquarium (represented by the colored rectangles). Diagram 3 illustrates the use of an approximately 130- μ m thick Mylar sheet that created an air pocket for blast mitigation in the third experiment. The rightmost diagram, 4, shows the aquarium rotated 90°. This change made it possible to have only air between the charge and the aluminum plate.

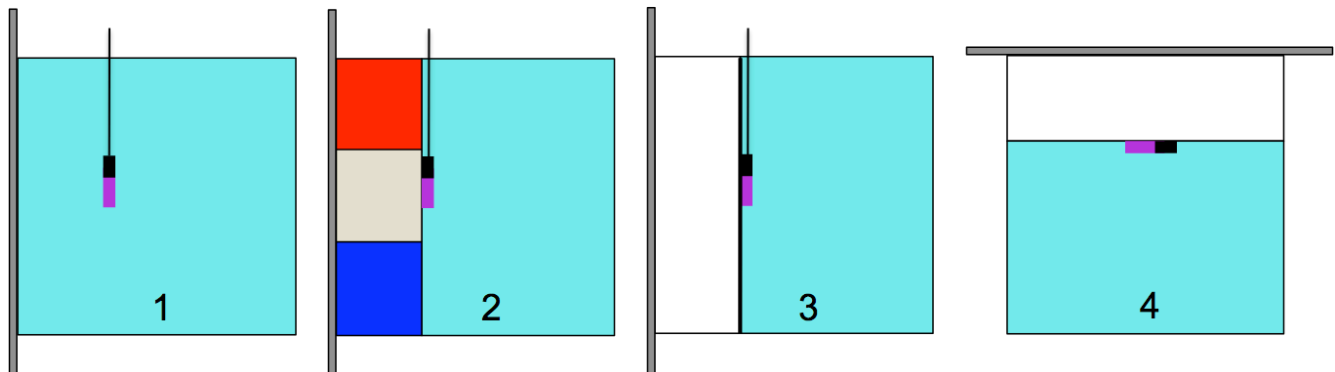


Figure 1. Side-view diagrams of the four small aquarium assemblies demonstrating the various blast mitigation techniques observed with DIC system: 1) no mitigation, 2) air-filled plastic tubes stacked in an array about 7-cm thick extending the full height of the aquarium, 3) air-pocket created with the use of a Mylar sheet (~130- μ m thick), 4) air, achieved by turning the structure on its side. In all four scenarios the explosive charges are represented by the purple rectangles and the detonators are represented by the black rectangles.

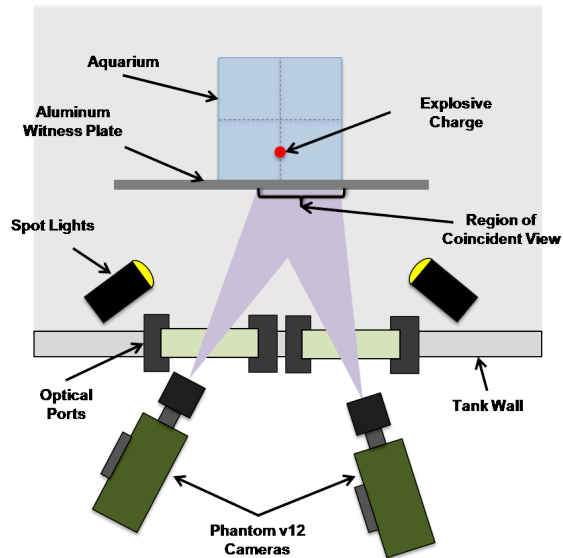


Figure 2. Diagram showing the experimental layout used for the small aquarium shots that incorporated DIC. Note that the diagram is not to scale.

All four small aquarium shots were conducted in the Gun Tank in the High Explosives Applications Facility (HEAF) at LLNL. The Gun Tank is a large blast chamber that has several ports located on its side in which 38.1-mm quartz windows were installed to allow video capture of the explosive event. Two Vision Research Phantom v12 cameras were setup outside of the chamber so that they each could view the area of interest of the aluminum plate. Fig. 2 shows a diagram of the small aquarium shot setup highlighting the general relationship between the explosive assembly, the tank wall, the spot lights, the optical ports and the cameras. Also, the diagram shows the region selected for coincident view. Note that the diagram is not to scale.

The Phantom v12 cameras have a fixed selection of frame rate versus resolution options. The relationship is such that as the cameras acquire images at higher speeds the available resolution decreases. For example, at a frame rate of 20,978 frames per second (fps) the best resolution available is 512 pixels by 512 pixels while at a rate of 66,997-fps the best resolution is 256 by 256. This inverse relationship made resolution vs. frame rate optimization necessary. For the small aquariums an adequate frame rate was estimated to be ~40,000 frames per second, a rate at

which the cameras could acquire images with a maximum resolution of 256 by 512 pixels. This rectangular viewing area presented us with the opportunity to either look at the whole plate with significant wasted viewing area around the edges, given that our target was square, or to assume half-symmetry about the vertical axis centered on the horizontal axis. After considering the boundary conditions and our desire to maximize the information we acquired the half-symmetry option was chosen.

Once the general area of interest was chosen our attention was focused on determining the appropriate speckle size. Given the size of the aquarium, viewing half of it encompassed an area about 13-cm wide by 26-cm tall. This meant that we had 256 pixels distributed over 13-cm, making each pixel account for 0.26-mm^2 ($0.51\text{-mm} \times 0.51\text{-mm}$). Our goal was that each spot in our speckle pattern would be at least 3 pixels (1.5-mm) across so we chose to produce a stencil that had many randomly drilled 3-mm holes. The stencil was made from a thin aluminum plate that had hundreds of holes drilled through it. The drilled plate had aluminum bar stock adhered to its edges to help keep it flat.

The 61-cm by 61-cm aluminum plates used as the target surface for the DIC were prepared prior to each shot using a multi-step process. The first step used was an alodizing treatment. This was done in an effort to make the surface more susceptible to paint adhesion. The next step in the process was spraying a thin layer of white Rust-Oleum® flat white paint as the background. The final step in the process involved spraying flat Rust-Oleum® black paint through the stencil onto the white background. The stencil did not cover the whole area of interest so the stencil had to be moved around the area of interest and sprayed until the total area was covered. Fig. 3 is a sequence of images showing different stages in the small aquarium shot sequence. Image 1 shows a section of the 61-cm by 61-cm aluminum 6061-T6 plate speckled with Rust-Oleum® spray paint. Image 2 shows an image of the aquarium assembly illuminated in the blast chamber. Multiple spots of light coming from the 1000-Watt Altman 1000Q Follow Spotlights can be seen overlapping in an effort to evenly light the target. Image 3 is a Phantom camera image taken during the calibration sequence. Image 4 is a Phantom camera image of the prepared surface in place in the blast chamber prior to detonation.

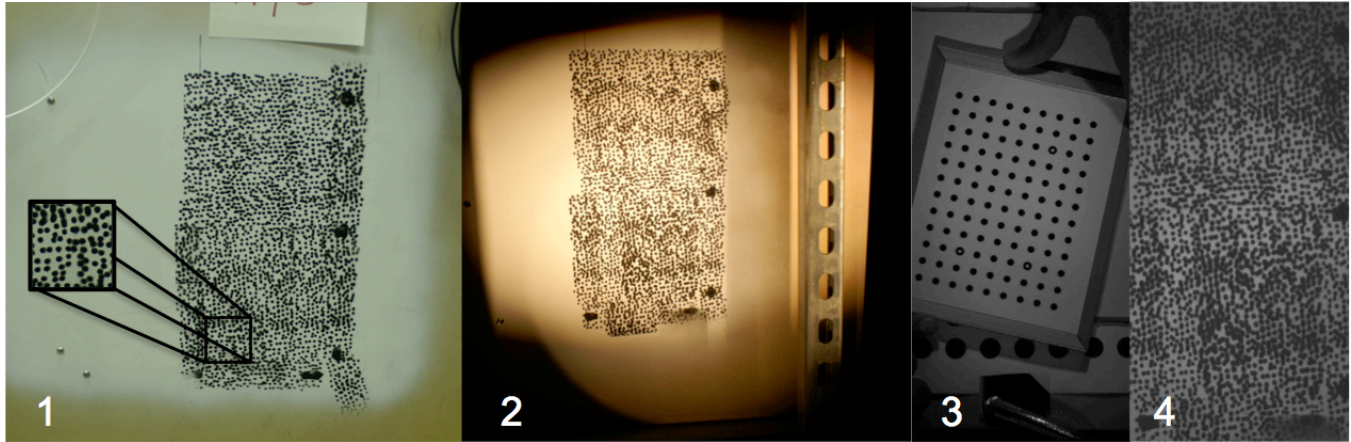


Figure 3. Images showing different stages in the small aquarium shot sequence. Image 1 shows a section of the 61-cm by 61-cm aluminum 6061-T6 plate speckled with Rust-Oleum® spray paint. Image 2 shows an image of the aquarium assembly illuminated in the blast chamber. Multiple spots of light can be seen overlapping in an effort to evenly light the target. Image 3 is a Phantom camera image taken during the calibration sequence. Image 4 is a Phantom camera image of the prepared surface in place in the blast chamber prior to detonation.

Large Aquarium Series: Set-up and Tank Configuration

The second series of experiments consisted of the large aquarium version of the explosive assembly. Similar to the small aquariums the large assembly was made up of a five-walled container, four walls of which were made out of 9.5-mm thick Lexan and the fifth wall made out of 15.9-mm thick aluminum 6061-T6. The assembled container had a volume of approximately 265-liters. The aquarium was approximately 72-cm wide by 55-cm tall. The aluminum plate used as one side of the aquarium was 1.22-m wide by 1.22-m tall. The plate had holes drilled through it so that when it was assembled the Lexan portion would be centered. Like the small aquarium version the aluminum plate was reinforced with Unistrut® beams.

LX-14 was also the explosive material used in the large aquarium experimental series. The charges in this case weighed about 146.5-g and were in the shape of right-circular cylinders. The explosive charge was positioned 17.5-cm from the aluminum plate. In the first large experiment no mitigation was used between the explosive and the aluminum plate. In the second experiment air-filled plastic tubes were used as the mitigation type.

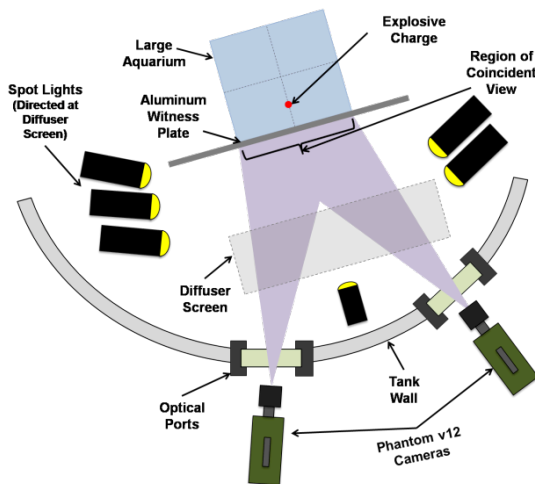


Figure 4. Diagram showing the experimental layout used for the large aquarium shots that incorporated DIC. Note that the diagram is not to scale.

The two large aquarium shots were conducted in the Spherical Tank in HEAF. Due to the increased size of the assembly and the need for extra space for additional lighting, the Spherical Tank was used because it had a more accommodating layout for our experiments. Like the Gun Tank, the Spherical Tank had 38.1-mm thick quartz optical ports installed to allow video capture of the explosive event. The ports on the Spherical Tank are located 45° apart around the spherical center of the tank. The Phantom cameras were setup outside of the tank and were focused so that they each were viewing the same area of interest of the aluminum plate. Fig. 4 shows a diagram of the large aquarium shot setup highlighting the general relationship between the explosive assembly, the tank wall, the spot lights, the optical ports and the cameras, with the noted difference from the small series that the lights were primarily reflected off of a diffuser screen prior to illuminating the target. This was done because illuminating the target with direct lighting resulted in uneven illumination with significant glare.

The length of the event for the large aquariums was calculated to take longer than the event for the small aquariums and thus a

slower frame rate was deemed acceptable. Lowering the frame rate made it possible for us to increase the resolution from 256 x 512 to 512 x 512. The frame rate of 20,978 fps was available at the resolution of 512 pixels by 512 pixels. Having a square field of view with the cameras allowed us to image the whole plate.

The plate preparation used for the large plate was different than the technique that was used for the small plates. Instead of using spray paint 3M Controltac™, which is a thin, white, adhesive-backed film, was used. This material was purchased to use in conjunction with a large printer but it turned out that the ink was not compatible with the Controltac™ surface. Instead of printing the speckle pattern from a computer file, the speckle pattern was drawn by hand by several of the authors of this paper. Prior to the addition of the permanent black ink speckling, the white surface was buffed to remove some of its gloss. After buffing the surface of the Controltac™ the speckle pattern was applied using the same principle as was used with the small aquariums, i.e., each speckle should be at least 3-pixels wide. Next, the film was cut in half and applied to the freshly cleaned surface of the aluminum witness plate, one side at a time, making sure that no bubbles or creases were formed during the application process.

The large area of interest and relatively low resolution made calibration somewhat difficult. When imaging a small area with a low resolution (due to high frame rates) one has the option of reducing the frame rate and increasing the resolution to calibrate the camera system. This has the benefit of getting crisp calibration images that can be used to calibrate the system even though the actual event will be captured at a much lower resolution (effectively looking at a small portion of the pixels). When imaging large objects, like these aquarium assemblies, the technique of increasing the resolution is not as practical. Instead, Correlated Solutions, Inc. Target Generator Software was used to create a large (50.8-mm between dots) calibration grid. The grid was printed out on a large printer and adhered to a 46-cm by 66-cm thin, flat plate of steel. The large-scale grid was then used as the traditionally used smaller grids are in other applications to calibrate the system. Fig. 5 show a sequence of images taken during the setup of one of the large aquarium shots. Image 1 is a photograph of the plate prior to final assembly but after the adhesive film had been applied. Image 2 shows a photo from one of the Phantom cameras taken during the calibration process. Image 3 is a picture from one of the Phantom cameras prior to the initiation of the explosive material.

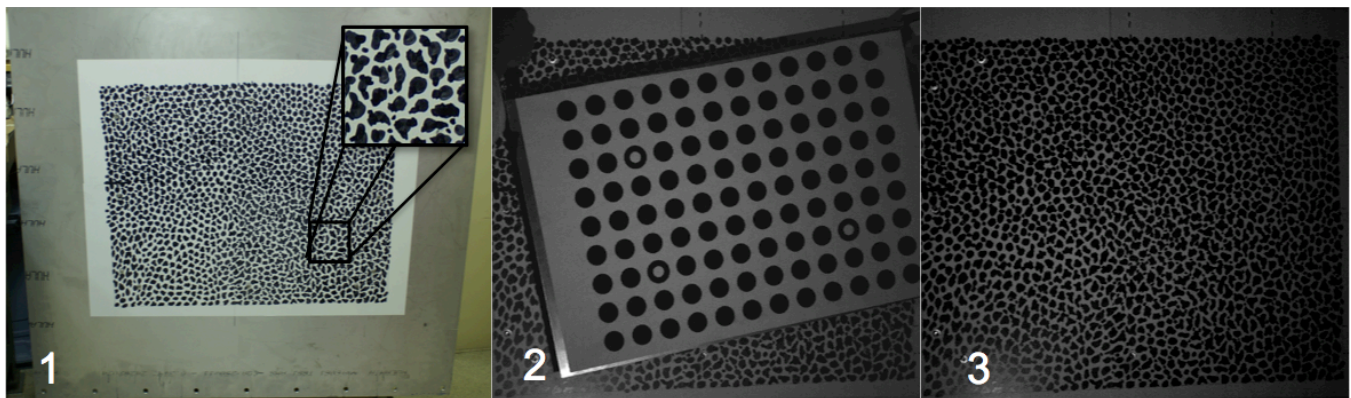


Figure 5. Images showing different stages in the large aquarium shot sequence. Image 1 shows the 1.22-m by 1.22-m aluminum 6061-T6 plate with the speckled 3M Controltac™ adhesive film attached. Image 2 shows an image from one of the Phantom cameras during the calibration sequence using a large array of calibration dots from Correlated Solutions, Inc. calibration software. The large dot array was printed on white paper and adhered to a large flat steel plate. Image 3 is a Phantom camera image of the prepared surface in place in the blast chamber prior to detonation.

RESULTS

Each attempt to use DIC as a diagnostic to watch the aluminum plate portion of the aquarium deform during the explosive event resulted in an abundance of useful data. Included in the results are output data files that include information regarding full-field displacement information, strain, strain-rate and velocity. The displacement data came in the form of color contour files that had the ability to have any point or group of points interrogated

independently and plotted one experiment versus the other. A selection of output resulted have been selected to shown the breadth of data acquired during this experimental series.

For the first three aquarium tests the out-of-plane displacement (w) was measured across a lineout taken at the mid-point of the plate as shown in Fig. 6. The lineout data was available at every frame but for the sake of comparison has been chosen at 0.1, 0.3 and 0.5-msec and is plotted also in Fig. 6. For the first and third small aquarium tests the paint on the plate nearest the explosive charge spalled off as a result of the displacement wave. The paint spall resulted in some localized loss of data but the overall picture of the displacement phenomena remained clear. The unmitigated shot (#1) and the air pocket/Mylar (#3) shots experienced significantly more deformation than did the air-filled plastic tube mitigated shot (#2). Due to the boundary conditions present in the experiments the plate rigidly moved during the deformation event. However, Vic3D, the Correlated Solutions, Inc. Software was used to remove the rigid body displacements prior to plotting the data shown below.

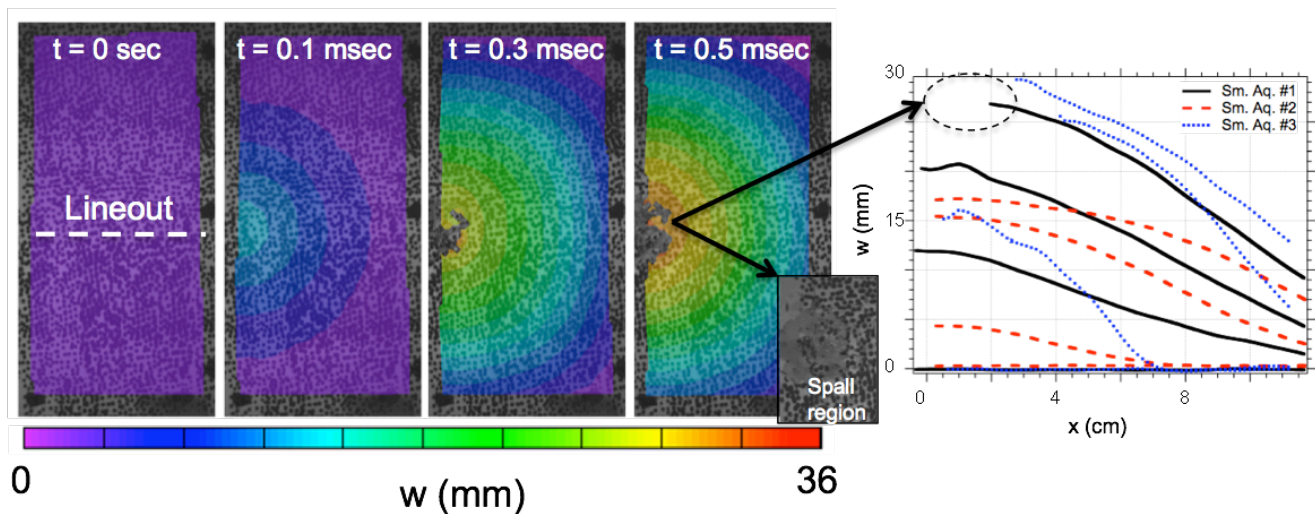


Figure 6. Color contour images showing the displacement progression in Small Aquarium #1, the unmitigated shot, alongside the lineout of out-of-plane displacement data in millimeters for the three small aquarium shots. A small region of paint spall is also shown inset in the figure and correlated with an area of data loss in the plot on the right bound by the dashed oval.

Out-of-plane displacement data was also collected for the large aquariums shots and is shown in Fig. 7. In the figure the top row shows the w -displacement in millimeters at 0.5-msec intervals for the first 1.5-msec of the unmitigated large test. The bottom row of the figure shows the analogous data for the air-filled plastic tube mitigated test. Both data sets are shown on the same scale and the magnitude differences are quite clear. The fact that the maximum w -displacement occurs around 1-msec is also clear in both image sequences.

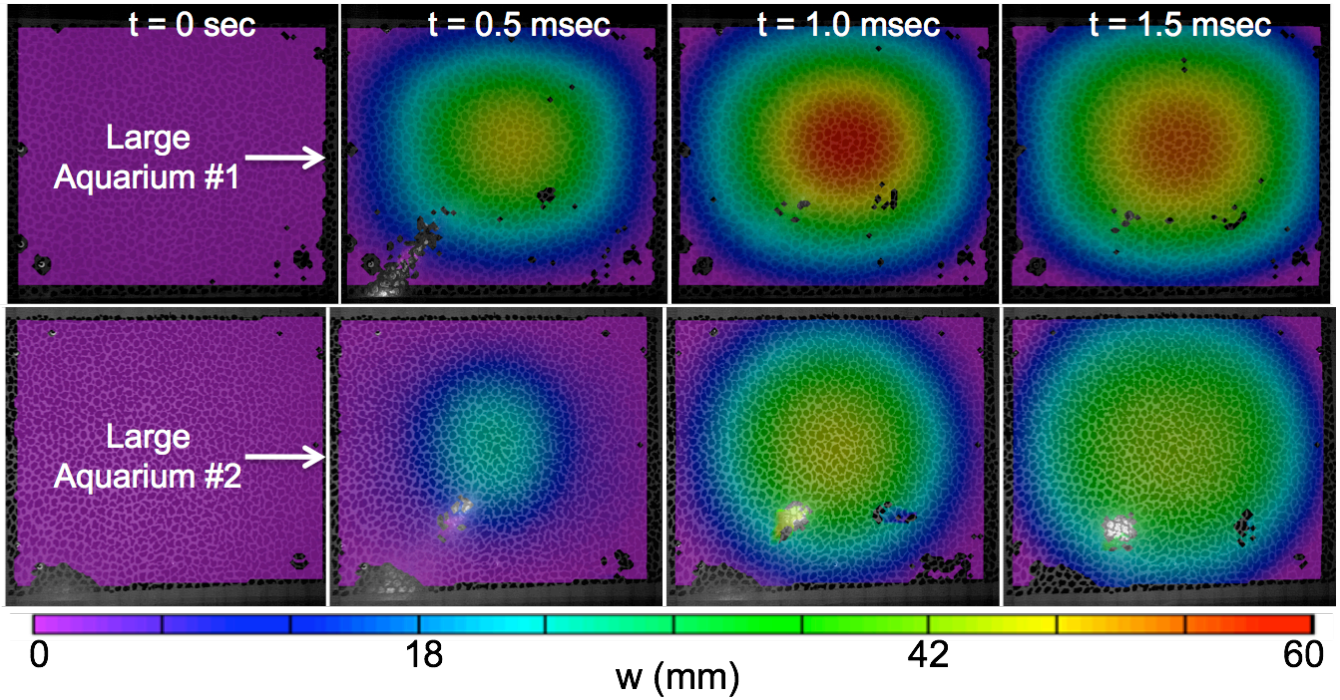


Figure 7. Comparison of the color contour output plots for Large Aquarium #1 and #2 over the first 1.5-msec of the deformation event. The top row shows the displacement results for Lg. Aq. #1, which had no mitigation in the water between the explosive charge and the aluminum plate. The bottom row shows the displacement results for Lg. Aq. #2, which had air-filled plastic tubes stacked in an array between the explosive charge and the aluminum plate.

In addition to the full-field data shown in the color-contour plots, data from a small region near the center of the two large aquarium shots was extracted and compared. The out-of-plane displacement, the strain, and the velocity are all plotted in Fig. 8 as a function of time. In all cases the unmitigated shot shows a greater effect from the explosive blast than the mitigated shot.

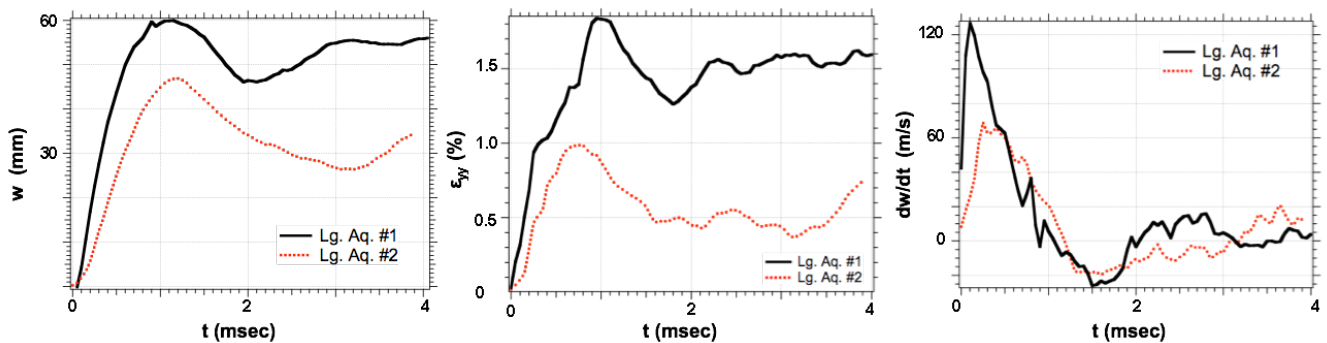


Figure 8. Displacement, w (mm), strain, ϵ_{yy} (%) and velocity, dw/dt (m/s) for a small region taken from the central location of each of the aluminum plates used in the Large Aquarium tests.

Post-test permanent deformation measurements of the witness plates were also acquired using the DIC system. The measurements were possible through the use of a projector hooked up to a lap top computer, a computer image file that had a random, high contrast speckle image and standard DIC components (e.g. cameras and software). The system was calibrated as usual and then the static images were taken and correlated. The correlation resulted in the spatial dimensions of the plate from which the shape could be determined. The measurement was done for all of the plates and the permanent deformation from each plate was compared to the

other plates that had used different blast mitigation techniques. Fig. 9 shows an example of the Large Aquarium #1 imaged in two ways. The first, shown on the right, included the view of the entire plate. This included regions of the plate not witnessed during the deformation event and areas of the plate outside of the region immediately connected to the aquarium. The second view, shown on the left, was a reduced view of the larger plate and corresponds with the area adjacent to where the aquarium was located. Each view provided information that was useful to the modelers.

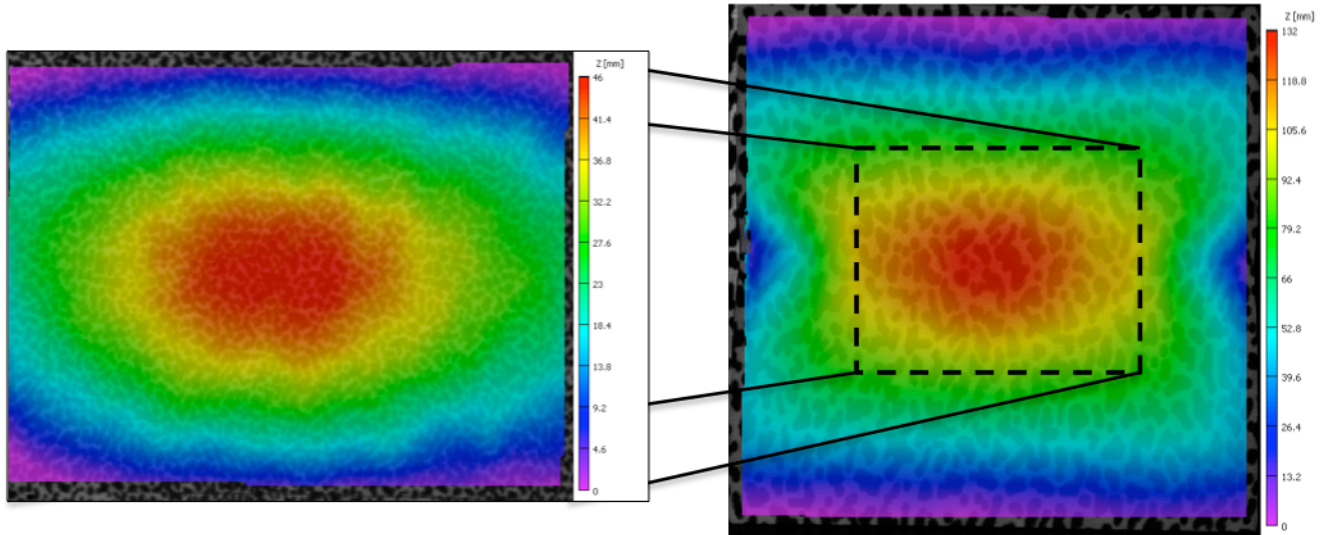


Figure 9. Two views of the post-test, static plate shape showing the full plate (on the right) and the central region closest to the aquarium (on the left). Each image has its own scale, set appropriately to demonstrate the amount of deformation seen in each case.

DISCUSSION

The six experiments reported in this paper show the effectiveness of digital image correlation for deformation events captured at rates from 20,000-40,000 fps. The out-of-plane deformation seen in the small aquarium shots was on the order of tens of millimeters and peaked in about 0.5-msec. The unmitigated shot and the air-pocket mitigated shot showed the most deformation in the small aquarium series. These results showed that the air-filled plastic tubes provided the best mitigation technique. The application of a speckle pattern using the spray paint technique was effective in that it resulted in a nicely contrasted image that did not have glare issues. The application was not technically challenging although the fabrication of the stencil and the application of the paint was time consuming. The biggest drawback to the paint technique was that in cases of unmitigated or under-mitigated blasts the paint spalled off the surface. The loss of paint resulted in the loss of data in the centermost region of the plate. While it was undesirable to lose this data the general displacement trend is still clear in the data.

The large aquariums were prepared using the 3M Controltac™ speckle technique. As mentioned previously, this method was done to avoid paint spall and so that the speckle pattern could be printed from a computer file. However, due to film and ink mismatch the automatic printing was not possible. This fact led to the need to hand speckle, which resulted in a well-controlled speckle pattern that took a long time to prepare. The glossiness of the Controltac™ also proved to be a challenge and required that the surface be buffed with an abrasive prior to speckling in an effort to reduce the glare. The high intensity lights located in close proximity to the surface resulted in cases of uneven lighting and a lot of glare. The solution to the problem of uneven lighting and glare was the introduction of a diffuser screen. This helped even the lighting and reduce the glare although it did not fully eliminate the glare. In order to get enough light on the target surface one of the more wide-angled lights was left directly pointed at the target. This did not prove to be an issue until the plate began to move as a rigid body after the blast impact. As the plate moved forward, pivoting and translating, the glare from the light began to interfere with the images in localized areas. Like the data loss from the paint spall, the glare caused localized data loss, but unlike the paint spall the data loss was not in the central region of the plate. In addition, the large aquariums were viewed in their entirety instead of using half-symmetry so the deformed plate stayed in the region

of coincident view longer than the deforming small aquarium plates. The deformation data, the strain and the velocity data were obtained for the large aquarium shots. The maximum out-of-plane deformation ranged between 40 and 60-mm with the unmitigated shot showing much more displacement than the shot done with air-filled plastic tube mitigation. The velocity and strain magnitudes were likewise diminished in the case of the air-filled tube mitigation.

SUMMARY

Six high-speed explosively driven deformation events were imaged with Phantom cameras and analyzed using digital image correlation. The details of the experiments including tank assembly and the preparation of the aluminum plates viewed with the cameras were discussed. Displacement, strain and velocity data were acquired for the small series and large series of aquarium shots. The data showed that air-filled plastic tube blast mitigation technique was superior to no mitigation and also to air mitigation. The benefits of spray paint speckling and hand drawn speckling were discussed as well as the drawbacks associated with each technique. Post-test static plate measurements were performed and example data was shown.

ACKNOWLEDGEMENTS

The authors would like to thank LLNL's Dan Greenwood, Frank Garcia and Greg Silva for their assistance with the operation of the cameras, the development of proper lighting conditions, assembly preparation and the calibration of the digital image correlation system. Discussions with David Backman of the National Research Council of Canada were also very helpful.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

REFERENCES

1. Nansteel, M. W. and Chen, C. C., "High-Speed Photography and Digital Image Correlation for the Study of Blast Structure Response," *ITEA Journal*, Vol. 30, pp. 45-56, 2009.
2. Neuberger, A., Peles, S. and Rittel, D., "Scaling the response of circular plates subjected to large and close-range spherical explosions. Part I: Air-blast loading," *Int. J. of Impact Engineering*, Vol. 34, pp. 874-882, 2007.
3. Neuberger, A., Peles, S. and Rittel, D., "Scaling the response of circular plates subjected to large and close-range spherical explosions. Part II: Air-blast loading," *Int. J. of Impact Engineering*, Vol. 34, pp. 859-873, 2007.
4. Tiwari, V., Sutton, M. A., Shultis, G., McNeill, S. R., Xu, S., Deng, X., Fournery, W. L. and Bretall, D., "Measuring Full-field Transient Plate Deformation Using High Speed Imaging Systems and 3D DIC" *Proceedings of the SEM Annual Conference*, Albuquerque, NM, June 2009.
5. Reu, P. L. and Miller, T. J., "The Application of High-Speed Digital Image Correlation," *J. of Strain Analysis*, Vol. 43, pp. 673-688, 2008.
6. Reu, P. L. and Miller, T. J., "The Application of High-Speed and Ultra-Speed Digital Image Correlation," presented at the SEM Fall Conference, Columbia, SC, 2009.